Development of an Integrated Control System Using Notebook PC Batteries for Reducing Peak Power Demand

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Abstract -In this paper, we propose an integrated control system that reduces peak power demand by using the internal batteries of notebook PCs. The system forecasts multiple power demand curves based on the power consumption of an office, and plans a charging/discharging schedule for each PC battery by considering the forecasts and information about the notebook PCs. By controlling the charging and discharging of PC batteries, the system reduces the peak power demand without restricting usability. We also evaluated the efficiency of peak power demand reduction in the simulation experiments and during field testing.

Keywords: Peak power demand reduction, control of charging and discharging, internal batteries of notebook PCs, demand forecasting, and optimization.

1 INTRODUCTION

To address power supply shortages resulting from the impact of the Great East Japan Earthquake, Japan's energy conservation regulation was revised to reducing just peak power demand from reducing overall power demand. In the future, it is anticipated that numerous energy storage devices will be placed in a wide range of locations, such as buildings and houses. Therefore, there is greater need for a mechanism to enable peak power demand reduction by charging energy storage devices (storing energy) during off-peak periods and discharging them (utilizing stored energy) during the peak time.

Here, to save power urgently, the use of the internal batteries of notebook PCs is attracting attention. This is because early dissemination of energy storage devices is difficult in terms of cost and operation, while lots of notebook PCs already exist in offices and homes. In the summer of 2011, many computer manufacturers released peak shift applications that can control the charging and discharging of a notebook PC battery. Figure 1 shows the peak shift setting utility released by Fujitsu Limited [1]. Such application charges and discharges a PC battery during periods each specified by the PC user. In this paper, "discharge a PC battery" means "force a notebook PC to be powered by its battery." Therefore, if these applications discharge PC batteries during the peak time and charge them during off-peak periods, we can save the power consumed by notebook PCs during the peak time and reduce the peak power demand.

This approach, however, has two problems. First, in a small-scale environment like an office, power consumption

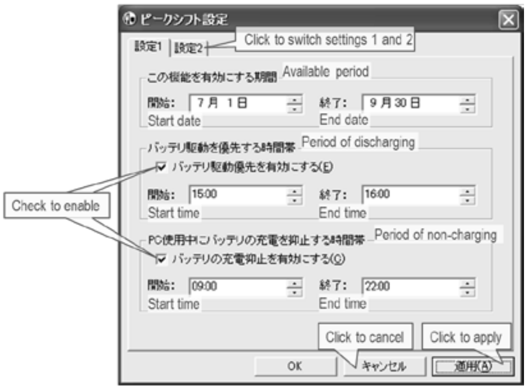


Figure 1: Peak shift setting utility released by Fujitsu Limited.

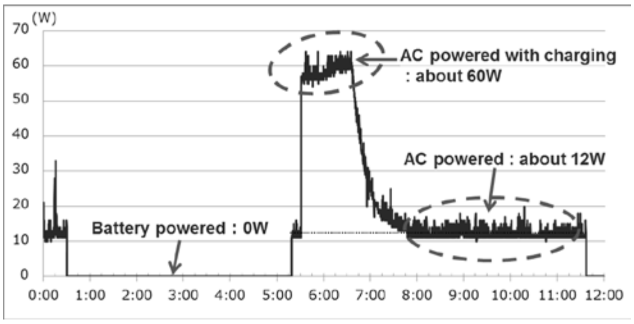


Figure 2: Power consumption of a notebook PC.

will change significantly depending on the number of users and electronic devices utilized, making it difficult to accurately forecast such fluctuations and decide when to charge and discharge PC batteries. In addition, since the power consumed during charging of a PC battery is very high (see Fig.2), there is a risk of increasing the peak power demand when multiple notebook PCs charge their batteries at the same time. Also, frequent charging/ discharging and long-term discharging of a PC battery may cause the battery to deteriorate and be empty when needed (e.g., outside).

In this paper, we propose an integrated control system that reduces the peak power demand without restricting usability by controlling the charging and discharging of PC batteries based on the power consumption of an office. The reminder of the paper is organized as follows. In section 2, we propose an integrated control system. In section 3, we present the implementation of the proposed system and give the evaluation results after using the implemented system. In section 4, we discuss some related works; then in section 5, we conclude the paper.

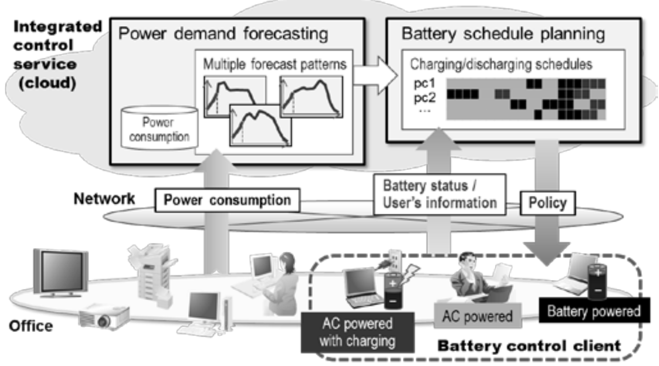


Figure 3: System schema.

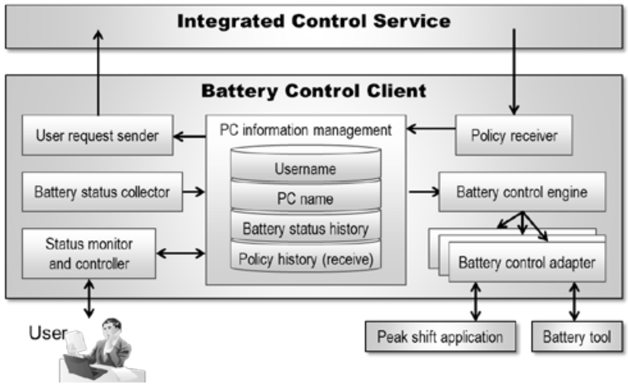


Figure 4: Architecture of battery control client.

2 INTEGRATED CONTROL SYSTEM

An overview of the integrated control system is given in Fig.3. The system consists of a battery control client that works at each notebook PC and an integrated control service that works as a cloud-based service.

The battery control client periodically collects the PC battery level and the user's information, and sends them to the service. The client also controls the charging and discharging of the PC battery based on the received policy (the control information to charge and/or discharge the PC battery) from the service. The client does all these things without any help from the PC user.

On the other hand, the integrated control service collects data sent by clients and the office power consumption data over a network. Based on the collected data, the service performs power demand forecasting and battery schedule planning, and sends the policy to each client. Here, the cloud-based service has the advantages of ensuring data collection and integrated control, and easily applying to multiple offices.

In the following, we further explain the battery control client, the integrated control service, and two algorithms to solve the problems described in section 1.

2.1 Battery Control Client

Figure 4 shows the architecture of the battery control client. The function of each module is as follows.

1. PC information management
   This module manages the following information on the battery control client.
   - **Username:** The username of the PC user.
   - **PC name:** The hostname of the notebook PC.
   - **Battery status history:** The history of battery statuses collected at [2. Battery status collector].
   - **Policy history (receive):** The history of policies received at [4. Policy receiver].
2. Battery status collector
   This module periodically collects the power configuration (battery powered / AC powered / AC powered with charging), the battery level [%], and the remaining battery lifetime [sec]. The module stores them together with the present time in [1. PC information management].
3. User request sender
   This module sends to the service the username, the PC name, the latest battery status (these are managed at [1. PC information management]) and the present time. The module periodically sends them in order to help the service to grasp information about the connecting clients.
4. Policy receiver
   This module receives a policy from the service, and stores it and the receipt time in [1. PC information management]. The module also notifies [5. Battery control engine] of the policy.
5. Battery control engine
   This module transfers the notified policy to one of [6. Battery control adapter] which is available at the notebook PC, except in cases in which control is temporarily suspended.
6. Battery control adapter
   This module controls the battery tool that charges and discharges the PC battery based on the transferred policy. Since there are many battery tools (include peak shift applications), this module masks the differences among them and is transparent to [5. Battery control engine].
7. Status monitor and controller
   This module shows the PC user the change of state (a service is connected or a policy is received), the current status of the PC battery, and the control status. The module also accepts user instructions for temporarily suspending and resuming control, and terminating the client.

2.2 Integrated Control Service

Figure 5 shows the architecture of the integrated control service. The function of each module is as follows.

1. Information management
   This module manages the following information on the integrated control service.
   - **Power consumption history:** The history of power consumption collected at [2. Power consumption collector].
   - **Demand forecasting history:** The history of forecasts (power demand curves) and their related parameters created at [3. Power demand forecaster].
   - **User request history:** The history of user requests received at [4. User request receiver].

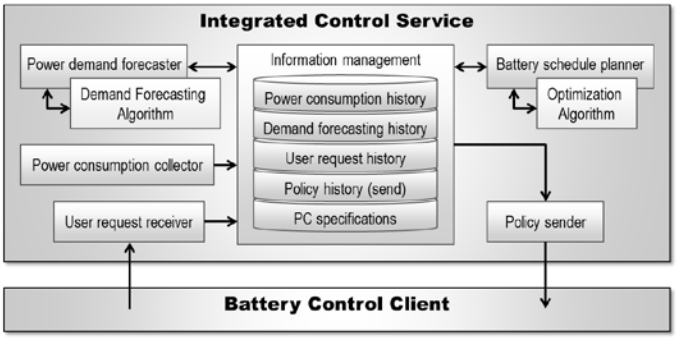


Figure 5: Architecture of integrated control service.

- **Policy history (send):** The history of policies sent at [6. Policy sender].
- **PC specifications:** The following specifications of notebook PCs with which the clients will work.
  - *Power consumption of each power configuration* (battery powered / AC powered / AC powered with charging) [W]
  - *Battery capacity* [Wh]
  - *Maximum battery level* [%]:
    The highest battery level to which a PC battery can be charged. By setting the level lower than 100, the system prevents the PC battery from being fully charged (a factor that accelerates battery deterioration).
  - *Minimum battery level* [%]:
    The lowest battery level to which a PC battery can be discharged. By setting the level slightly higher, the system prevents the PC battery from being discharged for a long time which might make it empty when needed
  - *Starting battery level* [%]:
    The highest battery level at which a PC battery can start to charge. By starting to charge only at a lower than specified level, the system prevents the PC battery from being repeatedly charged and discharged (a factor that also accelerates battery deterioration).
  - *Charging and discharging battery curves*:
    The curves showing the relation between the elapsed time and the battery level, where a PC battery is charged/discharged.

2. Power consumption collector
   This module periodically collects current power consumption and stores it together with the present time in [1. Information management].
3. Power demand forecaster
   This module forecasts multiple power demand curves by invoking the demand forecasting algorithm described in subsection 2.3.
   - **Inputs**: All daily power consumption (these are managed at [1. Information management]).
   - **Outputs**: Multiple power demand curves and their related parameters (these are to be stored in [1. Information management]).

   The module periodically performs this procedure because the size of the power consumption history increases with time.
4. User request receiver
   This module receives user requests from clients, and stores each of them and their receipt times in [1. Information management].
5. Battery schedule planner
   This module plans charging/discharging schedules by invoking the optimization algorithm described in subsection 2.4.
   - **Inputs**: Power consumption of the day, latest forecasts and their related parameters, PC specifications, and user requests (these are all managed at [1. Information management]). To ensure peak power demand reduction, the PC specifications and the user requests are limited to those of the connected clients, where a connected client denotes the client that has sent the user request to the service within a set period.
   - **Outputs**: Charging/discharging schedules for PC batteries of the connected clients.

   After planning schedules, the module creates a policy for each connected client from the corresponding schedule, and notifies [6. Policy sender] of the policy. The module periodically performs these procedures because users carry around their own notebook PCs and connected clients vary over time.
6. Policy sender
   This module sends a client the notified policy, and stores it together with the present time in [1. Information management]. The module performs these procedures when the policy is notified not only from [5. Battery schedule planner] but also from other external programs.

2.3 Demand Forecasting Algorithm

In a small-scale office, as described in section 1, power consumption will change significantly depending on the number of users and electronic devices utilized, making it difficult to forecast a power demand curve in a simple way. Moreover, since the service plans charging/discharging schedules based on a forecast, a wrong forecast may increase the peak power demand by charging PC batteries during the peak time.

Therefore, the demand forecasting algorithm forecasts the multiple power demand curves of the day. As shown in Fig.6, the algorithm initially classifies daily power consumption based on the peak time and the range of power consumption in the daytime. Using Ward’s Method [9], daily power consumption is classified into five patterns, i.e. a pattern in which power consumption during the morning, before noon, early afternoon, and evening is high, and a pattern in which power consumption does not vary much throughout the day. Then, the algorithm calculates the Euclidean distance between daily power cnsumption and the power consumption of the day, and extracts the similar days in which the Euclideand distance is short. Finally, the service calculates the power demand curve and the parameter for each classified pattern. In this paper, the power demand curve of a pattern is the hourly-averaged power consumption of the extracted days in the pattern, and the parameter is the ratio of the extracted days in the pattern.

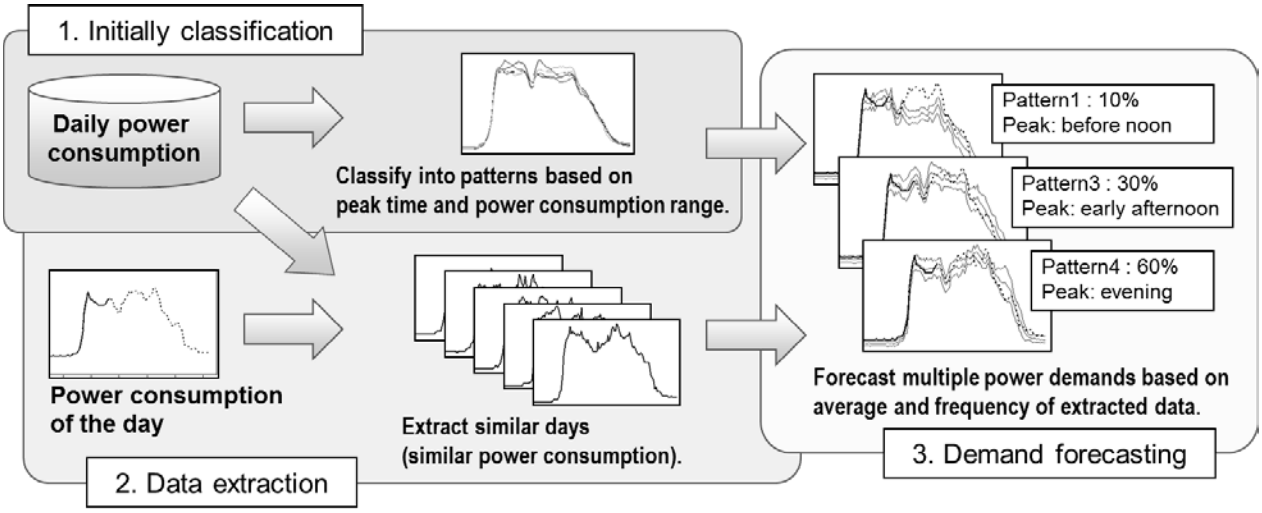


Figure 6: Diagram of demand forecasting algorithm.

Since the service plans charging/discharging schedules based on multiple forecasts, it can handle any potential level of power consumption and reduce the peak power demand even in a small-scale environment like an office.

2.4 Optimization Algorithm

To reduce the peak power demand for power using PC batteries, it is necessary to efficiently control the charging and discharging of them based on power demand. Moreover, not to restrict usability, the service has to prevent PC batteries from deteriorating and being empty when needed.

Therefore, the optimization algorithm regards the planning schedules as a multi-objective combinatorial optimization problem and finds approximate solutions using a local search algorithm as follows.

- **Objective functions (**listed in order of priority**):**
  1. Minimizing the peak power demand.
  2. Maximizing battery levels of notebook PCs at the end of the day. This function makes the service charge PC batteries to prepare for peak power demand reduction of the following day.
  3. Minimizing the overall power demand. This function indirectly prevents PC batteries from deteriorating by not charging and discharging more than necessary.
  4. Maximizing the minimum power demand. Combined with 1., this function balances the power demand.
  5. Minimizing the number of times power configuration is switched. This function also improves the usability.
- **Constraints:** The features of the PC battery including the variation and the range of the battery levels. The range constraint prevents PC batteries from being empty.
- **Solutions:** The power configuration of each notebook PC at each time interval of the day.

In each iteration, the local search algorithm chooses one solution from candidates by comparing the values of each objective function in order of above priority order (the lexicographic order). Specifically, the algorithm chooses the solution with the lowest peak power demand, and it chooses the one with the highest battery levels only when the peak power demands of all candidates are same. The detailed algorithm is proposed in Ref.[4].

Using the optimization algorithm, the service can reduce the peak power demand without restricting usability. Moreover, by setting the constraint based on each user's usage pattern, the service can keep higher battery levels for notebook PCs which are frequently used without a power supply (e.g., when the PC users are out of the office), and prevent PC batteries from being empty when needed.

3 IMPLEMENTATION AND EVALUATION

We implemented the integrated control system described in section 2, and evaluated the efficiency of peak power demand reduction using the implementation. In the following, we describe the implementation details of the system, and the results of simulation experiments and field testing.

3.1 Implementation Details

We implemented the battery control client as a Java application on Windows. We also implemented two battery control adapters that control the peak shift setting utility (Fig.1) and the Fujitsu system extension utility that supports system extension functions for Fujitsu notebook PCs. To facilitate usability, the client automatically starts on logon and puts its icon in the system tray. It also shows a message balloon during a state change, a tooltip of the current status when the PC user hover the pointer over the icon, and a control menu when the PC user right-clicks the icon.

On the other hand, we implemented the integrated control service as a Java servlet running on Tomcat 6.0. The service obtained the office power consumption data from the ftp server that collected data from each power distribution board. We also implemented the demand forecasting algorithm as an R script and the optimization algorithm as a Java plug-in.

3.2 Simulation Experiments

We evaluated the ideal efficiency of peak power demand reduction. For this purpose, we used the power consumption of our office on a weekday in August, 2011, and regarded it

Item		value
Power consumption [W]		
	AC powered	12
	AC powered with charging	60
	Battery powered	0
Battery capacity [Wh]		63
Maximum battery level [%]		100
Minimum battery level [%]		20
Starting battery level [%]		89

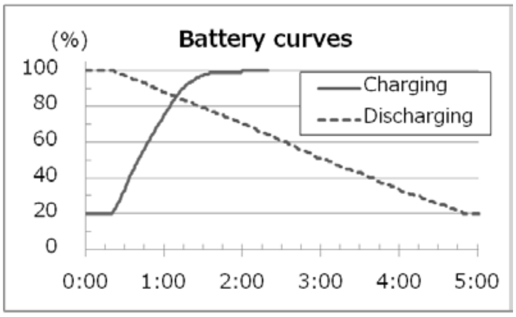
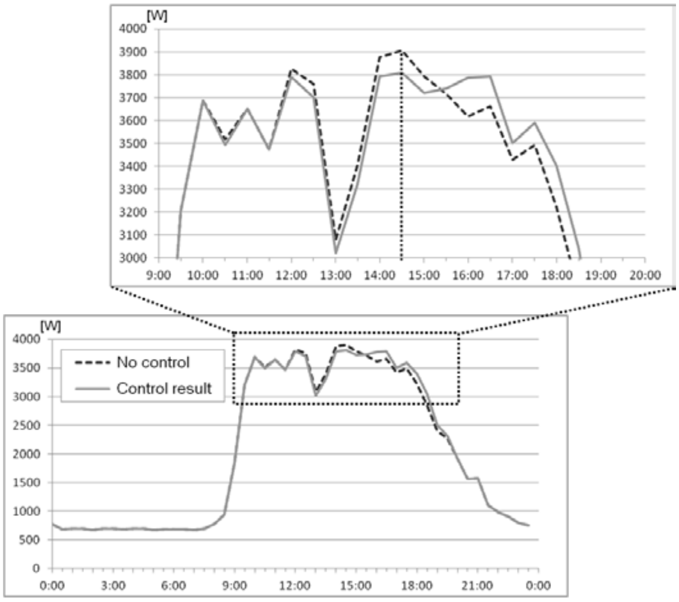
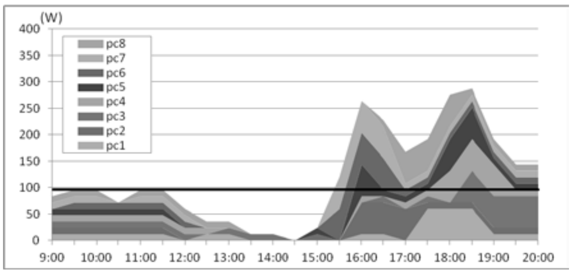


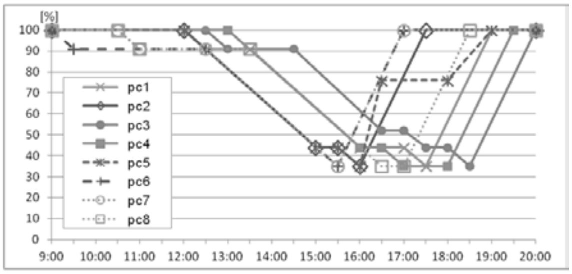
Figure 7: Specifications of a notebook PC (Fujitsu LIFEBOOK A561/C).



(a) Office power demand.



(b) Power consumption of notebook PCs.



(c) Battery level of each notebook PC.

Figure 8: Effectiveness of peak power demand reduction.

as a forecast (in other words, the service did not invoke the demand forecasting algorithm).

We simulated the power consumption after controlling the charging and discharging of PC batteries according to the planned schedules. We assumed that there were *N* controllable notebook PCs and that they had the uniform specifications described in Fig.7. Here, the power consumption of each power configuration was measured using the smart power strip [6], and the charging and discharging battery curves were created by periodically measuring the battery level while charging and discharging the PC battery. In addition, we assumed that the service controlled the charging and discharging of a PC battery only from 9:00 to 20:00, for example assuming that users put their own notebook PCs in the locked box after work for security reasons.

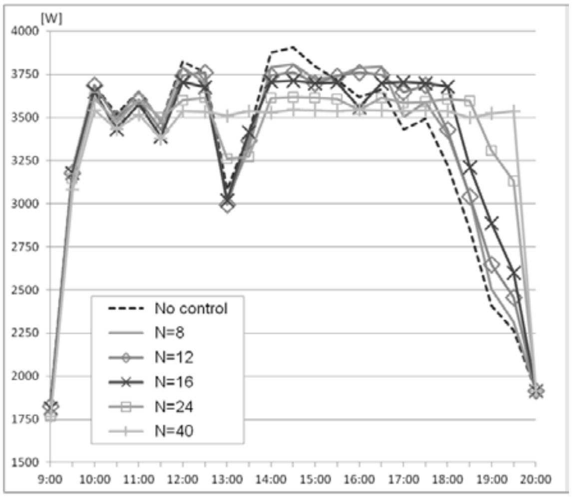
3.2.1. Effectiveness of the System

First, we examined the experiment where *N* (the number of controllable notebook PCs) is 8. Figure 8 shows the simulation results. In these graphs, the horizontal axis indicates the time. The vertical axes indicate the office power demand, the power consumption of the notebook PCs, and the battery level of each notebook PC, respectively.

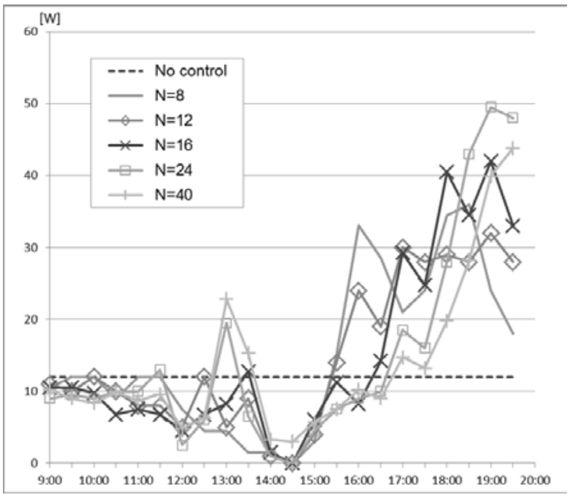
In Fig.8(a), the peak power demand is reduced 96W (about 2.5%) from 3906W to 3810W. In Fig.8(b) and (c), at the peak time (14:30), the system discharges all PC batteries and saves the most power, in other words, the power consumed by the notebook PCs is 0W. Moreover, at the time of the 2nd highest peak power demand (12:00), the system also discharges some PC batteries and saves some power in order not to exceed the reduced peak power demand. After 15:30, the system charges the PC batteries that have low battery levels because of discharging. Even though the controllable time range is restricted, the system can charge all PC batteries to 100% without exceeding the peak power demand. The overall power demand is increased 240Wh (about 0.5%) from 48032Wh to 48272Wh due to the loss of energy by charging and discharging PC batteries.

3.2.2. Effects of *N*

Next, we examined the experiments while changing *N* from 8 to 40. Figure 9 shows the office power demand and



(a) Office power demand.



(b) Average power consumption of each notebook PC.

Figure 9: Effects of number of controllable notebook PCs.

Table 1: Priority order of objective functions in each pattern.

Objective functions	Pattern			
	A	B	C	D
Minimizing the peak power demand	1	1	1	1
Maximizing battery levels of notebook PCs at the end of the day	2	5	2	2
Minimizing the overall power demand	3	**2**	4	4
Maximizing the minimum power demand	4	3	**3**	5
Minimizing the number of times power configuration is switched	5	4	5	**3**

the average power consumption of each notebook PC, respectively.

In Fig.9(a), as N gets larger, the peak power demand gets lower because the system saves more power by discharging PC batteries. Moreover, when N is 40, the system balances the power demand by charging the PC batteries at the time when the power demand is low (around 13:00).

In Fig.9(b), except when N is 40, the system discharges all PC batteries at the peak time and saves as much power as the system can. On the other hand, when N is 40, the system does not discharge all PC batteries at the peak time. This is because the power demand is balanced, and there is no time to charge the PC batteries that have low battery levels because of discharging. Actually, the amounts of the peak power demand reduction in the case when N is 8, 12, 16, 24, and 40 are 96W, 144W, 192W, 288W, and 360W, respectively, and when N is less than or equal to 24, the amount is proportional to N. These results also show that, in this office, the peak power demand is not reduced any more even when N is more than 40.

3.2.3. Effects of Priority Order of Objective Functions

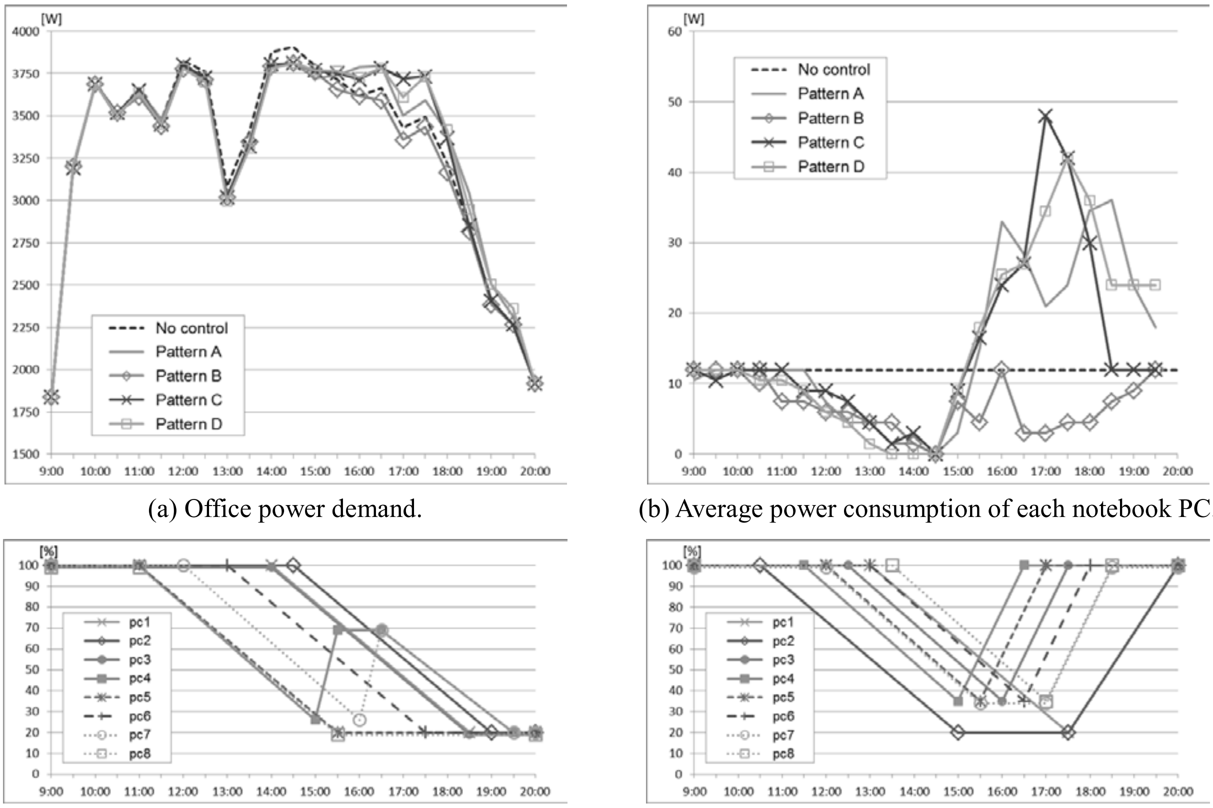
Finally, we examined the experiments while changing the priority of the objective functions as shown in Table 1. The order of a pattern A is the default priority order described in subsection 2.4. Figure 10 shows the office power demand, the average power consumption of each notebook PC, the battery level of each notebook PC in a pattern B, and that in a pattern D, respectively.

In Fig.10(a) and (b), the peak power demand in each pattern is reduced 96W (about 2.5%) by discharging all PC batteries at the peak time because orders of all patterns give the highest priority to "minimizing the peak power demand."

The order of a pattern B gives higher priority to "minimizing the overall power demand" than to "maximizing battery levels of notebook PCs at the end of the day." As a result, in Fig.10(c), the system charges very few PC batteries, and the power consumed by notebook PCs is always low shown in Fig.10(b). In fact, the overall power demand in a pattern B is reduced 444Wh (about 0.9%) from 48032Wh to 47588Wh. In this pattern, the system cannot reduce the peak power demand of the following day because all notebook PCs have low battery levels at the start of the day. However, the order of pattern B is effective in cases where PC batteries will be charged during that night and forecasts of the following day is low.

The order of a pattern C gives the highest priority to "maximizing the minimum power demand" in the lowest three objective functions. In spite of above priority order, the minimum power demand in a pattern C is the same as that in other patterns. However, since the system balances the power demand when N is large in subsubsection 3.2.2, we need to examine more experiments to evaluate the effect of this priority order in the case where N is large.

The order of a pattern D gives the highest priority to "minimizing the number of times power configuration is



(a) Office power demand.

(b) Average power consumption of each notebook PC.

(c) Battery level of each notebook PC (pattern B).

(d) Battery level of each notebook PC (pattern D).

Figure 10: Effects of priority order of objective functions.

Table 2: Specifications of notebook PCs used in field testing.

Item	pc1	pc2	pc3	pc4	pc5	pc6	pc7	pc8	pc9	pc10
Model name	A561/C			A540/C	S761/C			P770/B	S8490	S560/B
Power consumption [W]										
AC powered	11			11	10			13	22	14
AC powered with charging	70			65	79			68	89	70
Battery powered	0			0	0			0	0	0
Battery capacity [Wh]	63			56	67			63	63	63
Maximum battery level [%]	100	100	100	80	80	100	100	100	80	80
Minimum battery level [%]	20	25	23	20	40	40	40	40	40	40
Starting battery level [%]	89	89	89	69	69	89	89	89	69	69

switched" in the lowest three objective functions. As a result, in Fig.10(d), the system switches the power configuration as few times as possible. The order of a pattern D is effective to reduce the number of times the screen brightness changes and user stress occurred by above changes.

3.3 Field Testing

During the period from September 21th to October 20th, 2011, we conducted field testing at our office of 40 employees. The service obtained the power consumption data of our office. There were 10 notebook PCs with which the battery control clients worked during the field testing. Table 2 shows their specifications (all Fujitsu LIFEBOOK series). Here, different from the simulation experiments, the power consumption of each power configuration is the value given in the product catalogs. In addition, the maximum and the minimum battery levels are set based on users' activities (e.g., the frequency of the use without a power supply). Table 3 shows the parameters and their values used in this field testing.

Figure 11 shows the result of one day. The upper graph shows the office power demand while the lower table shows the power configuration collected at each notebook PC at each time interval of the day. In the graph, the line indicates the forecasts, and the bars indicate the actual power consumption. In the table, the black cells, light gray cells and dark gray cells indicate whether the power configurations of the notebook PCs are battery powered, AC powered, or AC powered with charging, respectively.

Table 3: Parameter configuration.

		Parameter	Value
Battery control client			
	Battery status collector	Time interval of collecting battery status	1 minute
	User request sender	Time interval of sending user request	10 minutes
Integrated control service			
	Power consumption collector	Start time and time interval of collecting power consumption	8:44, 10 minutes
	Power demand forecaster	Start time and time interval of invoking demand forecasting algorithm	8:45, 30 minutes
	Battery schedule planner	Start time and time interval of invoking optimization algorithm	8:46, 30 minutes
		Time range of a charging/discharging schedule	From 9:00 to 20:00
		Time unit of switching power configuration	10 minutes
		Time period to define the connected client	15 minutes

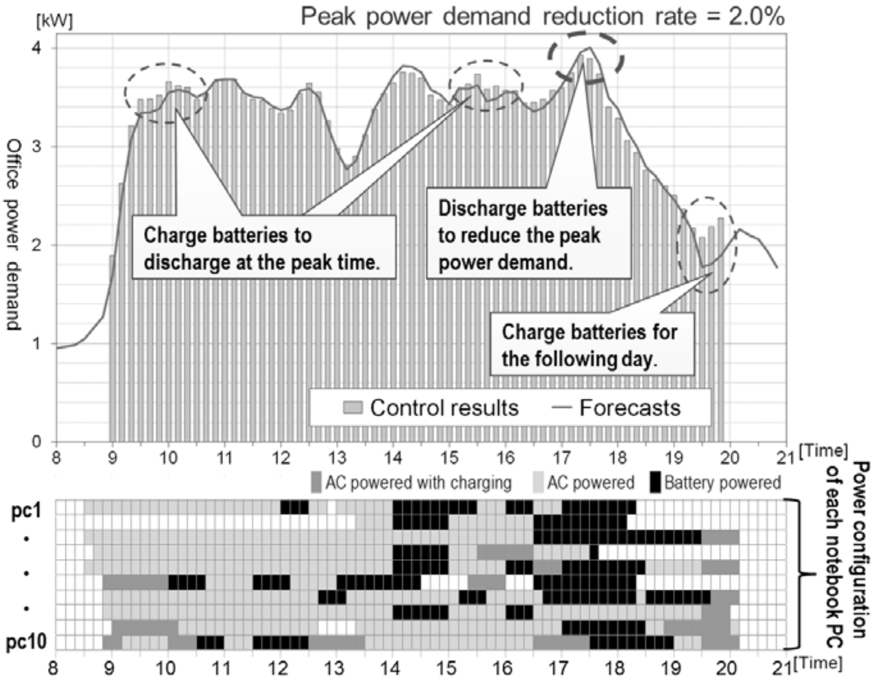


Figure 11: Result of a field testing.

Meanwhile, a white cell indicates the status in which the notebook PC does not connect to the service at the corresponding time due to a network disconnection or system power-off.

In Fig.11, the peak power demand was reduced 80W (about 2.0%) from 4006W to 3926W. At the peak time (17:30), the system discharged 9 PC batteries (except for the battery of pc8) and saved the consumption power of these notebook PCs. Moreover, at the 2nd peak time (14:10), the system discharged 6 PC batteries in order not to exceed the reduced peak power demand.

We analyzed the reason why the system did not discharge the battery of pc8 at the peak time. First, from 16:00 to 16:30, the user of pc8 attended a meeting and used pc8 without a power supply, making the battery of pc8 discharged regardless of the charging/discharging schedule (in other words, the system failed to control the battery of pc8). Moreover, because of the above discharging, the battery level of pc8 was less than its minimum battery level, and the system cannot discharge the battery of pc8 at the peak time. However, it also did not charge the battery for not increasing the peak power demand.

After 18:50, the system charged 6 PC batteries (all notebook PCs that charged their batteries were connected clients) to prepare for peak power demand reduction of the following day.

Here, the system charged several PC batteries before 18:50. We analyzed this result and found that these batteries can be separated into two groups. One group is the PC batteries with battery levels that are already low in the morning (e.g., the notebook PCs did not charge their batteries during the previous day or were used without a power supply during the last night). The other group is the PC batteries with battery levels that are also low because of discharging before the peak time. As a result, the system charged the PC batteries that had low battery levels so that they could be discharged at the peak time.

These trends occurred in other testing days even though the peak power demand and the power configurations of the notebook PCs were different during these days. Therefore, in any case, our system reduces the peak power demand by discharging PC batteries at the peak time.

4 RELATED WORKS

Until recently, while many studies on power demand forecasting have been made, most studies forecast the peak power demand for optimized operation of power generators and power supply stabilization. After the Great East Japan Earthquake, some studies forecasted the power demand curve for peak power demand reduction using energy storage devices. In [7], we proposed a forecasting method that forecasts the power demand curve with high accuracy. In this method, the curve is created by combining the power consumption of days which characteristics are similar to that of the forecasting day, and then revised based on the peak power demand forecasted by multiple regression analysis. These studies may forecast the wrong curve in our environment because, in their assumed environment, the law of great numbers is applicable and the power consumption does not change significantly.

Generally, an optimization problem such as a planning schedule can be solved as a mixed integer programming problem. In our assumed environment, however, it is difficult to solve as a mixed integer programming problem because there are minimax type objective functions and the symmetry of the problem is high. On the other hand, it is also difficult to find the global optimal solution by an enumerative method. In this paper, therefore, we found approximate solutions using a local search algorithm. The detailed algorithm is proposed in [4].

Some studies on the control system of energy storage devices have been made for not only reducing the peak power demand but also for the compensation of power demand. In [5], the authors proposed a compensation system that controls the charging and discharging of the lithium-polymer batteries based on whether or not the provided power is larger than the power demand. In [8], the authors proposed a supply/demand control system that plans the operation based on generation and demand forecasting by using a neural network and fuzzy systems. Since these studies do not assume other uses of the energy storage devices, the energy storage devices may be empty when needed, for example when needed during a power outage. Moreover, early dissemination of energy storage devices is difficult in terms of cost and operation as described in section 1.

Recently, many peak shift applications were released by computer manufacturers, such as Fujitsu Limited [1], IBM Japan [3], and NEC Corporation [2]. These applications can reduce the peak power demand by controlling the charging and discharging of a notebook PC battery. The following are parameters of the peak shift setting utility [1] as shown in Fig.1. (Other applications also need similar setting.)

- **Available period:** The start and end dates. During this period, the utility enables control.
- **Period of discharging:** The start and end time of discharging. During this period, the utility forces the notebook PC to discharge its battery, i.e., to be powered by its battery.
- **Period of non-charging:** The start and end time of non-charging. During this period, the utility does not allow the notebook PC to charge its battery.

However, in most applications, these parameters need to be set manually by a PC user. Although the peak shift setting tool [2] can set these parameters by considering the power demand forecasted by electric power companies, it may increase the peak power demand because the forecasted power demand is almost different from the office power demand.

5 CONCLUSION

In this paper, we proposed an integrated control system (a battery control client and an integrated control service) that controls the charging and discharging of PC batteries based on the power consumption of an office. The integrated control service performs power demand forecasting and battery schedule planning based on the collected data, and sends the policy (the control information) to each client. On the other hand, the battery control client controls the charging and discharging of its battery based on the received policy from the service.

We evaluated the efficiency of peak power demand reduction in the simulation experiments and during field testing. From the results, at the peak time, the system discharges many PC batteries and reduces the peak power demand about 2.5% in a simulation experiment (2.0% in field testing). Moreover, during off-peak periods, the system charges the PC batteries that have low battery levels because of discharging.

As part of our future work, we plan to extend the system and conduct additional field testing to verify the efficiency of peak power demand reduction in various office environments. We also plan to consider the control of the energy storage devices for deployment in smart cities.

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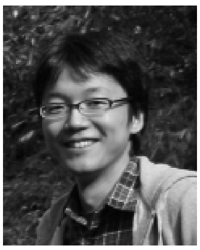

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